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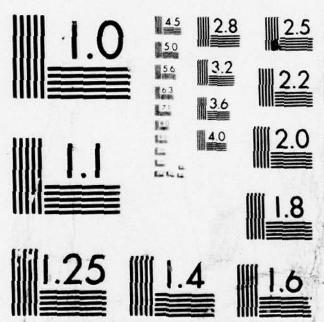
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(12) LEVEL II

NRL Memorandum Report

Definition of Directional Wave Spectral Measurement Requirements for Active Microwave Sensors of Remote Ocean Surface Measuring System (ROMS)

D. T. Chen

Advanced Space Sensing Applications Branch
Space Science Division

August 1978

NAVAL RESEARCH LABORATORY
Washington, D.C.

78 10 11 041

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NRL Memorandum Report 3818

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
(6) Definition of Directional Wave Spectral Measurement Requirements for Active Microwave Sensors of Remote Ocean Surface Measuring Systems (ROMS).

5. TYPE OF REPORT & PERIOD COVERED
(9) Final Report, on one phase of task

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
(10) Davidson T. Chen

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
U.S. Naval Research Laboratory
Washington, DC 20375

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
NRL Problem G01-10, 62759N
Proj. WF 52-553-000

11. CONTROLLING OFFICE NAME AND ADDRESS
Naval Air Systems Command
Washington, DC 20361

12. REPORT DATE
(11) August 1978

13. NUMBER OF PAGES
53

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)
(14) NRL-MR-3818

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited

(12) 54 p.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)
(16) F52553
(17) WF52553000

18. SUPPLEMENTARY NOTES
(18) SBIE (19) AD-E000 242

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Remote ocean surface measuring systems	Ocean surface information
Wave forces	Internal Waves
Currents	Directional wave spectra
Sensor performance requirements	Wave prediction
	Accuracy requirements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

One of the primary requirements for the active microwave sensors of the Remote Ocean Surface Measuring System (ROMS) is the measurement of directional ocean wave spectra. The measurement accuracy requirements on various applications, which are relevant and essential to the Navy's needs are delineated based upon their physical significance, detectability and physics involved. The sensor performance requirements in order to meet the required measurement accuracies are also derived based upon the sensor's precision, → (over)

DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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resolution, and accuracy in the measurements and the percentage of confidence in the processing techniques. The merge of the measurement accuracy requirements and the sensor performance requirements, necessary to meet these requirements on measurement accuracies, clearly link the theoretical and experimental scientific capabilities with those of the instrumental development, in this important area of concern, and from this established linkage a meaningful compromise between these two capabilities can be conjunctured with confidence.

CONTENTS

Definition of Directional Wave Spectral Measurement Requirements for Active Microwave Sensors of Remote Ocean Surface Measuring System (ROMS)

I. INTRODUCTION

One of the primary requirements for the active microwave sensors of the Remote Ocean-Surface Measuring System (ROMS) is the measurement of directional ocean wave spectra. In order to specify this requirement, particularly for the needs of our Navy, one should re-familiarize himself with several important subjects within the general context of the directional wave spectra. This report is written in such a way that the information on the directional wave spectra is inclusive and self-contained for ROMS. Then, the definition of directional wave spectral measurement requirements is delineated based upon the expected measurement capability of ROMS' active microwave sensors.

Various physical parameters which are relevant and important for the Navy will be discussed and their accuracy requirements subsequently, will be defined.

II. DIRECTIONAL WAVE SPECTRA

Almost all the surface waves in the ocean are generated by the wind. These waves propagate in different directions with different amplitudes, lengths, periods and phase angles. The resulting surface is always random so that the detailed description of the surface waves cannot be achieved in a deterministic manner in either space or time. The only alternative is to seek their properties by statistical means. The most important one of all the commonly used

Manuscript submitted June 28, 1978.

statistical measures is the directional wave spectrum which is the energy density function in terms of wave number vector or wave frequency with direction; therefore, the three-dimensional wind-wave spectrum has long occupied the center of interests in ocean wave study. The directional properties of surface waves are important not only from a practical point of view in application to wave prediction, description of mass transport phenomenon, evaluation of wave energy, wave impact and wave forces on coastal structure, etc., but also in the basic study of the detailed physical process involved in wave generation.

The definition of the three-dimensional wave spectrum can be stated simply as follows. Let the surface elevation of position $\vec{x}$ and time t be $\zeta(\vec{x},t)$. Then, $\zeta(\vec{x} + \vec{r}, t + \tau)$ is the representation of the surface elevation at position $\vec{x} + \vec{r}$ and time $t + \tau$. The correlation function $R(\vec{x}, t; \vec{r}, \tau)$ is defined as

$$R(\vec{x}, t; \vec{r}, \tau) = \overline{\zeta(\vec{x}, t)\ \zeta(\vec{x} + \vec{r}, t + \tau)} \tag{2.1}$$

where the overbar denotes ensemble average. Under the assumptions of stationarity and homogeneity, the correlation function defined in Eq. (2.1) is invariant with respect to the origin of the coordinate system in time or space. In other words, the correlation $R(\vec{x}, t; \vec{r}, \tau)$ reduces to $R(\vec{r}, \tau)$ which is a function of $\vec{r}$ and τ, the spatial and temporal separations respectively. The three-dimensional wave spectrum $X(\vec{k}, \sigma)$ of the wave number vector $\vec{k}$ and wave frequency σ is defined as the Fourier transform of the correlation function as

$$X(\vec{k}, \sigma) = (2\ \pi)^{-3} \int_{\tau} \int_{\vec{r}} R(\vec{r}, \tau) \exp\left[i(\vec{k} \cdot \vec{r} - \sigma\tau)\right] d\vec{r} d\tau \tag{2.2}$$

Simple as the definition is, there are difficulties in interpretation as well as in actual measurement of the wave spectrum. These difficulties are discussed below.

Strictly speaking, the conditions of stationarity and homogeneity can never be satisfied since sea state obviously depends on fetch and duration of the storm. However, without these assumptions, the statistical analysis of the sea surface would be difficult. Fortunately, the assumptions can be justified on physical grounds without too much sacrifice of mathematical rigor, since the typical wavelength of the order of several hundred meters is always small in comparison with the diameter of the storm, and the typical period of waves is of the order of several seconds which is much smaller than the duration of the storm. Furthermore, the correlation function of the waves decays and becomes negligible after several wavelengths or periods (Kinsman, 1960); therefore, the local region or time span can be regarded as statistically stationary. With these assumptions, however, an additional difficulty arises in the interpretation of the results. By rigorous spectral analysis, under the assumptions of stationarity and homogeneity, the three-dimensional wave spectrum still cannot be determined uniquely. This is explained as follows.

Through a simple translation of coordinates in space and time, from Eq. (2.1) we have

$$
\begin{aligned}
&\overline{\zeta(\vec{x}, t)\ \zeta(\vec{x}, \vec{r}, t + \tau)} \\
&= \overline{\zeta(\vec{x} - \vec{r}, t)\ \zeta(\vec{x}, t + \tau)} \\
&= \overline{\zeta(\vec{x}, t - \tau)\ \zeta(\vec{x} + \vec{r}, t)} \\
&= \overline{\zeta(\vec{x}, t)\ \zeta(\vec{x} - \vec{r}, t - \tau)} \qquad (2.3)
\end{aligned}
$$

i.e.,

$$
\begin{aligned}
R(\vec{r}, \tau) &= R(-\vec{r}, \tau) = R(\vec{r}, -\tau) \\
&= R(-\vec{r}, -\tau) \qquad (2.4)
\end{aligned}
$$

or $R(\vec{r}, \tau)$ is an even function in both $\vec{r}$ and τ. From Eqs. (2.2) and (2.4) the three-dimensional wave spectrum has,

also, to be an even function with respect to both $\vec{k}$ and σ, i.e.,

$$X(\vec{k}, \sigma) = X(-\vec{k}, \sigma) = X(\vec{k}, -\sigma)$$
$$= X(-\vec{k}, -\sigma) \tag{2.5}$$

Therefore, from Eq. (2.5) there is a 180° ambiguity in the information of the directional properties of the waves. This ambiguity in directional information arises from the assumptions of stationarity and homogeneity and forces the investigators to assume further that the energy distribution is confined in the half plane of $[-90°, 90°]$. That is, it is assumed that the waves propagate only with the local wind field; therefore, the energy spectrum on the other half plane of (90°, -90°) represents only the mirror image and can be folded back. This is a plausible assumption, indeed, but the true picture is much more complicated. Swells from other storms, waves generated by non-linear wave-wave interactions (Phillips, 1960; Longuet-Higgins, 1962; Hasselmann, 1968), and wave-turbulence interactions (Batchelor, 1957; Phillips, 1959) are examples of other inputs. Severe alterations by the adverse wind (Phillips, 1969) ensures, however, that the contribution of these waves is small, but this portion of the energy is, nevertheless, non-zero. Such information is, of course, lost in the artificial statistical folding of the spectrum.

Another difficulty is the limitation of the measurement and processing of appropriate data. By definition, in order to obtain the continuous three-dimensional wave spectrum in terms of wave number vector and wave frequency, the correlation function should be a continuous function not only of the spatial separation $\vec{r}$, but also the temporal separation τ. A continuous measurement in τ at a fixed position is comparatively easy to obtain, but a continuous

measurement in $\vec{r}$ is rather difficult, much less continuous data in both $\vec{r}$ and τ and the task of analyzing the data is out of the reach of the most sophisticated techniques today. Consequently, available measurements are limited only to either the directional wave number spectrum or the directional wave frequency spectrum (Phillips, 1969). A dispersion relation between the wave frequency σ and the wave number $|\vec{k}|$ has to be used to relate the measured directional wave number spectrum and the directional wave frequency spectrum. Furthermore, in order to resolve the 180° directional ambiguity, additional physical information has to be added independently to specify the direction, but this can be done only for the predominant waves with well-defined crest lines.

In addition, there is the crucial problem of understanding the detailed mechanism of wind wave generation. Hampered by these difficulties in both theory and field measurement, researchers are testing semi-empirical approaches with various degrees of success. All the directional wave spectra obtained thus far comes as the result of field measurements taken by a set of particularly designed instruments limited in practicality and loaded with assumptions and approximations. The general practice is to assume that one can decompose or separate the directional wave spectrum into an angular spreading function to indicate directionality alone and a one-dimensional energy function to indicate energy magnitude. The angular spreading function can be found by spectral analysis of the measured data. There are several methods in obtaining the directional wave spectrum. These methods are briefly discussed below in an order which has nothing to do with their relative importance.

The first method is using stereo photography. This

method was suggested by Barber (1956) as a qualitative estimation of the directional wind wave spectrum. Later a group in New York University picked up the idea and carried out the well known Stereo Wave Observation Project (1957). Chase et al. (1957) and Cote et al. (1960) estimated the directional wave spectrum by analyzing the surface elevations converted from the chosen grid points from the stereo photographs. Uberoi (1964) simplified the process of obtaining data by using an optical computer in analyzing the stereo photographs of the Stereo Wave Observation Project.

This stereo photography technique had the advantage of having the continuous correlation function in terms of $\vec{r}$ which was essential for obtaining the continuous directional wave number spectrum; there were however, several shortcomings in addition to the 180° ambiguity in directional information which was inherent in the spectral analysis. First of all, only the correlation function in the spatial relation and not in the time relation can be obtained through the stereo photographs. Thus, in principle, only the directional wave number spectrum can be evaluated directly, but even this is not so certain because of the limitations on the size and the resolution of the stereo photographs. It is impossible for a single pair of photographs to cover a large area with enough longer waves so that the spectrum will contain low wave number information and, at the same time, reveal enough details of the shorter waves for the spectrum to cover the high wave number end as well. As the resolution of stereo photography increases, however, much more detailed information can be included and retained, and this method promises to offer, at this date, the best method of obtaining wave information.

The second method makes use of a number of wave

meters arranged in arrays. This method was first proposed by Barber (1954). Later, Barber (1961 and 1963) worked out several examples of measurements for a single band of wave frequencies. The same idea was also used by Konyayev and Dreyer (1965), Dreyer and Konyayev (1967), Tsyplukhin (1966) and Krylov *et al.* (1966), to study waves in relatively shallow water in the coastal region. Munk *et al.* (1963), also used this method to observe tidal waves in the deep ocean. In all these studies, the predominant waves are long crested and well defined and this is probably the only situation that the probe array method promises to provide reliable information.

The method has serious limitations for use in general wave studies. In order to deploy the probes, a stable platform must be found; this almost immediately rules out its application in deep water. Furthermore, it will be more difficult to cover a large area with probes dense enough to get better readings than from a stereo photograph. The results can, of course, give the direction of propagation of swells, but as far as the angular spreading function is concerned, this method can only provide qualitative information at best.

The third method in obtaining the directional wave spectrum is by making use of a floating buoy. This method was first suggested by Barber (1946) also, and was developed by Longuet-Higgins (1946 and 1955). The observations were made by the National Institute of Oceanography and results were presented by Longuet-Higgins *et al.* (1963), Cartwright (1963), and Ewing (1969). A floating buoy of 91.44 centimeters in diameter equiped with gyroscopes was used to measure wave amplitude and components of wave amplitude gradient as functions of time; then these quantities were converted to the first five coefficients of a Fourier

series representing the directional wave frequency spectrum. The detailed technique of the floating buoy method was described by Cartwright and Smith (1964). Because correlation techniques were not used, the directional wave frequency spectrum obtained did not have the 180° ambiguity in its directional information. However, there are some shortcomings. The buoy acts as a filter which filters out any wave with a wavelength comparable or smaller than the diameter of the buoy. More importantly, the basic principle of this method is to obtain the first five, and only the first five coefficients of the Fourier series which are supposed to represent the directional spectral function. Unfortunately, the convergence of the series has not been determined making the error induced by the series truncation unknown.

The fourth method in obtaining the directional wave spectrum is by deriving the directional wave spectral information from the measurements of orbital velocity and pressure. This method was pioneered by Nagata (1964). Measurements of the orbital motion in waves was achieved by means of electromagnetic current meters. Nagata studied the statistical properties of the fluid motion and proposed that the method be used to obtain the directional wave frequency spectrum. Bowder and White (1966) and Simpson (1960) later developed this method for the measurements. Suzuki (1968) utilized the same idea to analyze pressure and components of the wave force acting on a sphere immersed in water for the determination of the continuous directional wave frequency spectrum. The analysis was much the same as that used for the floating buoy. The first five coefficients of the Fourier series of the directional wave frequency spectrum could be obtained; therefore, it has the similar shortcomings.

There are other methods in obtaining the directional wave spectrum, such as Stilwell's (1969, 1974) optical analysis of the sun glitter on the transparency of a surface photograph taken by an airplane, but the results in the form of directional wave number spectrum require frequent and difficult calibrations.

However, the instruments used by all the methods for the measurements of directional wave spectra can be classified, according to their proximities to the ocean waves, as in-situ and remote-sensing types. The in-situ type of instrument is installed or placed in the ocean whereas the remote-sensing type is placed above and away from the ocean surface.

The in-situ type, such as wave probes, buoys, etc., senses ocean waves directly. And because of its location, this type of instrument is exposed to chemical and physical hazards from the oceanic environment so that its duration of operation is extremely limited. On top of this shortcoming, the high cost of its placement and maintenance alone will make its global application impractical. Nevertheless, this type of instrument is better for the purpose of research over a very limited area of ocean for a short period of time.

Naturally, not only because its synoptic capabilities of providing information, but also because its invulnerability from variations of the oceanic environment, the remote-sensing type of instruments, such as Radar, is better suited for global application. These types of instruments infer ocean waves indirectly through mathematical models which require detailed understanding, theoretically and experimentally, of the interactions between electromagnetic waves and ocean waves. The resolving capability of wave amplitudes in two-dimensional sense by these types

of instruments depends critically on this understanding and data processing capacity. With the current state-of-the-art of these types of instruments, for obtaining directional wave spectra, in terms of resolution in mind it is very important to identify what our fleets can gain in tactical and strategic warfares by knowing directional wave spectra with the required resolution. Thus, proper priority can be assigned for the development of an integrated program, of which ROMS is a part, for achieving the design goals.

III. INFORMATION INFERRED FROM DIRECTIONAL WAVE SPECTRA

Information which can be inferred from directional wave spectra and, also meet Navy requirements will be discussed in this section. The discussion on the information will include a brief description of the information, a simple explanation of the physics involved in inferring the desired information from the directional wave spectra, of the order of magnitude of the information with respect to the directional wave spectra, and of the resolution required for the measurements in order to deduce this information. The relative importance and the priority of the information, which are debatable, will not be discussed here.

The order of magnitude of the parameter associated with the directional wave spectra is defined in terms of the velocity potential, ϕ, as defined in Phillips (1969). The first order means that the velocity potential is to be the order of $a|\vec{k}|$ where a is the wave amplitude and $|\vec{k}|$ is the magnitude of the wave number vector, $\vec{k}$. The second order means that the velocity potential is to be the order of $(a|\vec{k}|)^2$. Similiarly, the nth order can be defined accordingly. Theoretically speaking, the higher the order of magnitude is, the weaker the physical phenomenon is presented, and, subsequently the more difficult

it will be to detect this phenomenon. The parameter $a|\vec{k}|$ is called wave slope and is a dimensionless parameter.

The information inferred from the directional wave spectra and presented below is arranged in its order of magnitude.

1. WAVE FORCES

Ocean waves exert dynamic external forces in the forms of pressure, impact, drag, inertia and moment on floating subjects such as surface ships. This type of problem concerns the Navy, as far as ship dynamics are concerned, mainly in two areas. The first area of concern is on the effects due to ocean waves on fleet operations, especially, the surface effect ship which launches surface-to-surface missiles while the ship is cruising at an extremely high speed. The second area of concern is how to improve ship's performance in stormy oceans. Although tremendous progress has been made recently in evaluating the transfer functions for ship's responses with respect to external forces, both of the above mentioned concerns cannot be resolved without real-time evaluations of ocean waves from which the external forces can be readily calculated.

Salvesen et al.(1970), developed the method for evaluating wave-induced external forces. In their analysis, viscous effects are disregarded and the fluid motion is assumed to be irrotational so that their derivation can be formulated in terms of potential flow theory. Wave forces are evaluated in terms of wave frequency, wave number, velocity potential of wave, ship speed and configuration. The first three terms, wave frequency, wave number and velocity potential of wave are all derived from oceanic conditions and can be further reduced to two independent variables which are wavelength (or wave number) and wave amplitude.

The ship acts as a filter and will only respond to waves whose wavelengths are comparable to and larger than ship's dimensions. Thus, the required accuracy of the measurement on wavelengths (or wave number) is quite subjective in each application. The required measurement accuracy on wavelength can only be intuitively defined to be 10 meters or smaller. This requirement will be discussed further in this report.

In the derivation of the accuracy requirements on wave amplitude for wave force, one should go back to the basic theorems of mechanics. By potential flow theory (Milne-Thomson, 1966), it is evident that magnitude of wave force is proportional to the square of the derivatives of velocity of wave. This means that the magnitude of wave force is indeed proportional to the square of wave amplitude. However, nonconservative dynamic components of wave force such as impact are still not included in the potential flow theory. The effects of these nonconservative components of wave force can sometimes, be very significant. In order to account for these nonconservative components by Hamiltonian Mechanics (Goldstein, 1962), one has to evaluate the total energy contained in the wave. Neglecting terms higher than the first order of magnitude since the contribution of these higher order terms to the wave energy is extremely small, the magnitude of total energy is proportional to the square of wave amplitude. Thus, it is obvious that wave force is indeed dependent on the square of wave amplitude and, without any loss of generality and rigorous of science, the accuracy requirement on wave energy can be used also on wave force.

From Phillips (1969) the total energy, E, contained in a wave per unit area of the wave motion can be expressed as

$$E = 1/2\ \rho g a^2 \tag{3.1}$$

where a is the wave amplitude, ρ is the sea water density, and g is the gravitational acceleration. Let E_ε be the total energy contained in the same wave component whose wave amplitude is $(a + \varepsilon)$, where ε is an error of measurement. From Eq. (3.1)

$$E_\varepsilon = \left[1 + 2\ (\frac{\varepsilon}{a}) + (\frac{\varepsilon}{a})^2\right] E = C_\varepsilon E \tag{3.2}$$

where

$$C_\varepsilon = 1 + 2\ (\frac{\varepsilon}{a}) + (\frac{\varepsilon}{a})^2 \tag{3.3}$$

Let the error of measurement, ε, be -0.5 meter or +0.5 meter, for example, the value of C_ε can be computed for various values of wave amplitudes as shown in Table 3.1. The value of C_ε should be very close to the unity in Eq. (3.3) in order to have meaningful evaluations of wave forces. As can be readily observed from Table 3.1, for $\varepsilon = \pm$ 0.5m, the calculations for wave forces need corrections if the dominant wave's amplitude is less than 10 meters. Furthermore, the sign of ε makes a lot of difference. This however, indicates the need to distinguish undermeasurements from overmeasurements.

Nevertheless, $\varepsilon = \pm$ 0.5m is indeed acceptable for a = 10m which, by Table 3.1, indicates an error of $\pm$ 10% for wave energy. This accuracy requirement on wave amplitude points out the ratio of ε to a to be $\pm$ 0.05, i.e., the error in the measurement of wave amplitude can only be $\pm$ 5% or better. Since the smallest wave amplitude and the shortest wavelength of ocean waves which are of the concern for the wave force calculation are 0.5m and 25m, respectively, this error allowable for wave amplitude cannot exceed $\pm$ 0.025m. Nevertheless, considering the order of magnitude of wave force at this extreme situation this

a \ ε	- 0.5 m	+ 0.5 m
1 m	0.25	2.25
2 m	0.5625	1.5625
5 m	0.81	1.21
10 m	0.9025	1.1025
20 m	0.950625	1.050625

TABLE 3.1 C_ε

allowable error for wave amplitude can be relaxed to absolute value of $\pm$ 0.1m.

2. SURFACE INFORMATION FOR MISSILES LAUNCHED FROM UNDERSEA

Ocean waves will exert forces on the missile while it is in the water and passing the air-water interface. These forces will cause the missile to deviate from its designed course so that mid-course corrections are necessary. However, if information on the ocean surface waves is known in advance, the submarine can make optional maneuvers to make the required course corrections a minimum.

Without elaborating the physics involved in the determination of these forces, it can be concluded that the order of magnitude and the accuracy requirements on the information provided in this case should be the same as those of the wave forces.

3. FLEET PROTECTION

Ocean waves reflect and scatter radar signals randomly. If these ocean waves are large, their effects will make the returned radar signals noisy enough so that radar scope shows a blurred image. This phenomenon is called "sea surface cluttering". Thus, the real target information is smeared or lost.

Ocean waves, also, generate water particle orbital velocity and pressure fluctuation significantly from the ocean surface down to the depth which is comparable to one wavelength of the dominant wave component. Their combined effects change the acoustic properties of sea water randomly in such a way that transmission of sound waves will be reflected, blocked, diffused, and scattered within this depth. Therefore, it is very difficult if not impossible, to use the sonar system to trace a submerged submarine within this depth, which can be 100 meters or more for a regular stormy sea.

Henceforth, stormy sea provides shelter for surface and submerged fleets from detection. In order to take advantage of this protection effect for the surface fleet where large wave amplitudes and large wave slopes, $a|\vec{k}|$, are desirable and necessary, the accuracy of measurements required for wave forces should be more than adequate, but for submerged fleet it is desirable to discuss this requirement a little bit further.

Two physical parameters have been mentioned to be important for submerged fleet's non-detection. One is the water particle orbital velocity and the other is the pressure fluctuation. For simplicity in explanation, let us take a wave component whose wave amplitude is a and wave number is $|\vec{k}|$. From Phillips (1969), the water particle orbital velocity, $\vec{U}_L$, with respect to depth will have the magnitude of the first order as

$$|\vec{U}_L| = \sqrt{g|\vec{k}|}\ a e^{|\vec{k}|z} \tag{3.4}$$

where z is the depth from the mean sea level. The magnitude of the pressure fluctuation, p_f, with respect to depth can be evaluated, also from Phillips (1969), as a quantity of the first order as

$$p_f = \rho g \zeta e^{|\vec{k}|z} \tag{3.5}$$

where ρ is the density of sea water, g is the gravitation acceleration, and ζ is the elevation of wave which is proportional to wave amplitude a. Notice that both $|\vec{U}_L|$ and p_f, from Eqs. (3.4) and (3.5) are quantities which attenuate exponentially with respect to depth, z. Besides the accuracy of measurement requirement for wave amplitude, a, there is also an accuracy of measurement requirement for wave number, $|\vec{k}|$. Whereas, by looking at Eqs. (3.4) and (3.5), the accuracy of measurement requirement for $|\vec{k}|$ is more stringent than that for wave amplitude, a, at

constant depth, z. However, since the dominant wave component whose wave amplitude is a_D and wave number is $|\vec{k}_D|$ is the major concern for Equations (3.4) and (3.5), the established measurement accuracy requirements on wave forces are indeed acceptable.

4. WAVE PREDICTION

There are two important aspects of the problem on wave prediction. The one aspect of the problem is the growth of waves at a particular location and the other aspect of the problem is the propagation and the dissipation of waves from one location to another.

The growth of waves at a particular location has to be based upon the theory of the generation of waves by wind. Inoue (1967) combined the Miles' shear instability theory (Phillips, 1969) with the Phillips' resonant theory (Phillips, 1969) such that when the sea begins to grow from calm conditions, the resonance mechanism predominates and later, as the wind velocity begins to increase, the shear instability mechanism becomes more dominant. The Phillips' theory essentially states that a resonance between the air-sea system can occur when a component of the surface pressure distribution moves at the same velocity as a free surface wave of the same wave number. The Miles' shear instability theory states that the mean rate of energy transferred from the parallel shear flow to the surface wave is proportional to the curvature of the wind profile and inversely proportional to the slope of the wind profile at the height where the mean wind velocity is the same as the phase velocity of the wave component. The growth of waves is expressed in the form of the directional spectrum in terms of three-dimensional air pressure spectrum, wind velocity profile above the air-sea interface, time and fetch.

The propagation of waves is also quite well understood, based on the work of Barber and Ursell (1948), Pierson (1952) and the study of Snodgrass et al. (1966) in the Pacific. There can be no doubt that each spectral component in a wind sea propagate at group velocity in an appropriate direction, according to its wavelength and that such components can be tracked on a great-circle route for a distance comparable to half the circumference of the earth, theoretically.

There remains the problem of how waves are dissipated at sea. If there was no dissipation mechanism, the spectrum of the waves on the open ocean would soon become isotropic, with spectral components travelling in all directions at nearly every point. This is observed not to be the case, and there is some process by which waves travelling against strong wind-generated seas are rapidly attenuated. The study of Snodgrass et al. (1966), on the propagation of waves from the South Pacific to the North Pacific found that the greatest amount of attenuation was right in, or near, the generating area and that the swell could then travel through the subtropical highs and the trade wind regions without very much additional loss. It seems that the primary reason for the dissipation of the waves is the turbulence generated by the breaking waves in a wind-generated area. An attempt has been made to model this effect by taking the simple theories proposed by Lamb (1952) for viscous attenuation and using an Austausch coefficient in its place that enhances this effect. The spectral components travelling against the wind will not receive energy from the wind and must undergo some form of dissipation. The dissipation is governed by the directional wave spectrum of the wind sea. Let σ be the wave frequency of a wave whose period is T. Then $\sigma = \frac{2\pi}{T}$,with

$$\frac{\Phi_D(\sigma,\theta)}{\Phi\ (\sigma,\theta)} = \exp\left[-78\sigma_\zeta(\sigma/2\pi)^4\right]^N \tag{3.6}$$

where $\Phi(\sigma,\theta)$ is a component travelling against the wind, $\Phi_D(\sigma,\theta)$ is the component after 2 hours of dissipation, σ_ζ, is the standard deviation of the wave spectrum, and N = 4 if θ is in the direction opposite to the wind, N = 3.5 if θ is $\pm$ 15° to the wind, N = 3 if θ is $\pm$ 30° to the wind, etc.

The generation, dissipation and propagation of waves are investigated primarily in terms of the directional wave spectra and their associations with wind; their order of magnitudes such as that of wave dissipation shown by Eq. (3.6) are first order theory. However, there is another aspect of wave theory that might possibly play a role in the modification of the spectrum of a wind sea. It consists of the theory given by Phillips (1960) on third-order interactions for intersecting trains of gravity waves and the extension by Hasselmann (1961, 1963a and 1963b). A number of laboratory experiments are required to answer some crucial questions. Nevertheless, it is important to point out that energy cannot be destroyed in such a process so it must reappear at some other frequency. Unless after it reappears at some other frequency, it is then removed by the process of wave breaking (Phillips, 1958), there is the tendency to make the directional spectrum nearly isotropic.

Finally, the character of the turbulence in the wind over the ocean should play an important part in determining the rate of growth of the waves. A great deal of theoretical work on turbulence has suggested that the drag coefficient and the roughness length depend on atmospheric stability and on the height of the sea present in that particular area. It would be highly desirable to develop a

better way to modify the growth of a wave spectrum on the basis of how high the waves are at the time of the observation and on the basis of the stability of the air over the water. Miles' theory states that the rate of growth of a particular spectral component is determined by the ratio of the curvature of the wind profile to the slope of the wind profile at that elevation above the sea surface where the phase speed of the waves equals the wind speed. Since the phase speeds observed in fully developed seas are considerably in excess of the winds measured at 10 meters above the surface, this means that knowledge of the wind profile over the water must extend both theoretically and observationally to elevations well over 150 meters. Also, since the wind profile changes its character as a function of stability, the rate of growth of different spectral components will be quite different depending upon how the particular ratio mentioned above compares to the ratio that would exist under neutral conditions. All of these requirements on the wind field for the purpose of wave prediction should be comprehended in conjunction with ROM's passive microwave instrument wind measurement capability.

Global wave prediction capability is an essential requirement for our operational Navy. The Fleet Numerical Weather Central in Monterey, California, has made great progress (Lazanoff and Stevenson, Private Communication) toward this capability. However, since wave prediction utilizes theory of the first order of magnitude, the accuracy of measurement requirements defined for wave force is acceptable.

5. CURRENT

Waves do change their characteristics both kinematically and dynamically whenever they encounter currents. This phenomenon of changes has not only been observed by

mariners for centuries, but has also been systematically detected from satellite with scanning radiometers as reported by Strong and DeRycke (1973). These observations, combined with the theoretical treatise on wave-current interactions, greatly increase the probability of inferring currents by using remote sensing as a means to observe the changes in ocean wave characteristics. In order to explore this possibility further, Huang et al. (1972), and Tung and Huang (1973) derived quantitatively the measurable physical parameters such as dispersion relationships, wave spectra, slope spectra, surface roughness, and wave height distribution for wind-generated gravity waves in various steady non-uniform currents. With the progress made recently in the field of remote sensing, these physical parameters should be readily observable remotely. Furthermore, based upon the finding of Long and Huang (1976a, 1976b), the same measurement concept and technique can be extended to the range of capillary-gravity waves. Their theoretical predictions were confirmed by the laboratory observations on the changes in kinematic and dynamic wave characteristics for this spectral range of waves with variable currents. Their studies strengthen the concept of determining currents by observing waves remotely.

However, all the studies mentioned above are for the cases of one-dimensional waves. Chen et al. (1973) investigated the case of directional fetch-limited wind-generated gravity waves on variable shear currents. The continuity equation is identically satisfied in that particular situation where the current, strictly speaking, is still one-dimensional. Chen and Bey (1977) subsequently, investigated the two-dimensional interactions by employing numerical integration techniques. Their results were presented in the form of directional wave spectra.

The interactions between waves and currents are magnitude of the second order. Theoretically speaking, it is desirable to infer the current velocity through the measurements of dispersion relation which is, however, an extremely difficult task. In reality it is feasible to infer information on current velocity through the measurements of the directional wave spectra.

Evaluation of the accuracy requirements on the measurements of the wave spectra for inferring currents should be based upon the theoretical derived results such as those presented by Chen and Bey (1977). However, their results were not straight-forward for the purpose of deriving these accuracy requirements. As a logical substitution, the theoretical derived one-dimensional theoretical results presented by Huang et al. (1972) are being used for delineating these requirements.

Let $\phi(n)$ be the one-dimensional wave frequency spectrum without the influence of current, for the wave whose wave frequency is n and $\bar{\phi}(n)$ be the one-dimensional wave frequency spectrum with the influence of current, U, for the same wave. Then, from Huang et al. (1972)

$$\frac{\bar{\phi}(n)}{\phi(n)} = \frac{4}{\left[1 + \left(1 + \frac{4Un}{g}\right)^{1/2}\right]\left[\left(1 + \frac{4Un}{g}\right)^{1/2} + \left(1 + \frac{4Un}{g}\right)\right]} \qquad (3.7)$$

where g is the gravitational acceleration. Eq. (3.7) can be illustrated by Figure 3.1. Let us assume that the errors introduced in the measurements for $\phi(n)$ and $\bar{\phi}(n)$ are the same. By definition

$$\frac{\bar{\phi}(n)}{\phi(n)} = \left(\frac{\bar{a} + \varepsilon}{a + \varepsilon}\right)^2 \qquad (3.8)$$

where $\bar{a}$ is the wave amplitude for the wave whose wave frequency is n with the influence of current U, a is the

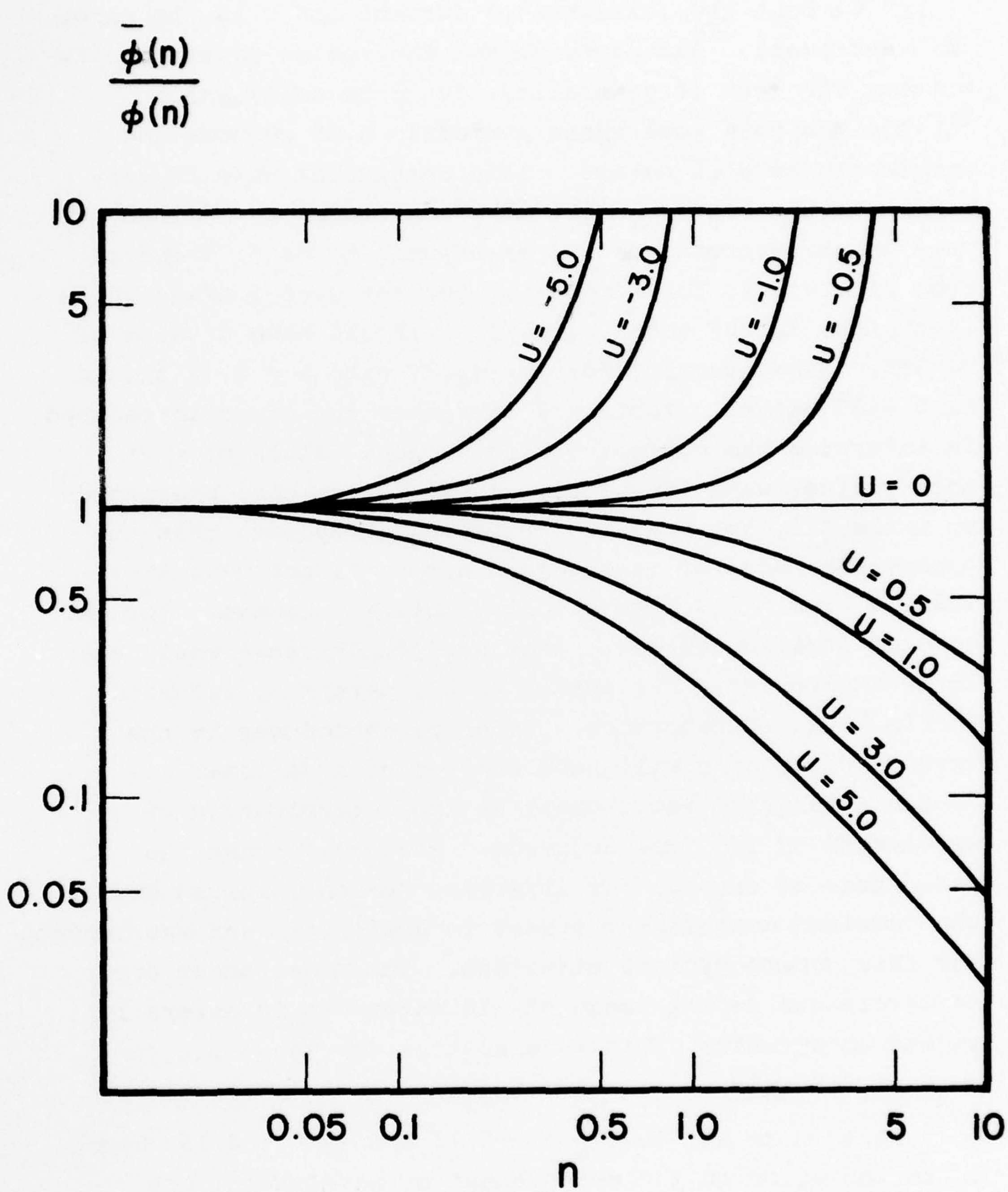


Fig. 3.1 - Relative changes of wave frequency spectra under different current conditions. U in m/sec and n in rad/sec.

wave amplitude for the wave whose wave frequency is also n, but without the influence of current and ε is the error in measurement. Furthermore, for the reason of simplicity without the loss of generality, let n be unity which corresponds to a wave whose period is 6.28 seconds and wavelength is 61.5 meters. This particular wave is very common in the ocean and its wave amplitude, a, limited by wave breaking processes can be assumed to be 0.75 meters. From Figure 3.1, for a positive current U of 1 m/sec which is typical in the ocean, $\overline{\phi}(n)/\phi(n)$ should have a value of 0.7356. Subsequently, for Eq. (3.8) with $\varepsilon = 0$, $\overline{a}$ should be 0.6433 meters. Table 3.2 tabulates the error introduced in inferring the current U with various values of ε at this typical wave frequency. Thus, in the case presented by Table 3.2, for practical purposes it appears that the acceptable range of measurement error, ε, for wave amplitude is from - 0.2 meters to 0.2 meters. However, for the case of negative current, this acceptable range would have to be smaller at - 0.1 meters to 0.1 meters by referring to Fig. 3.1. Furthermore, the error introduced in the determination of n will have exerted an additional acceptable range of requirement in the determination of wavelength by the same argument. Table 3.3 shows the percentage of errors, for inferring current, introduced by the combined measurement errors in amplitudes and wavelengths for this common typical situation. The measurement error in wavelength in the range of -10 meters to 10 meters is indeed acceptable. This is also true for the negative current situation.

This is to say that $\frac{\varepsilon}{a} = \pm\ 0.13$ and $\frac{\varepsilon_L}{L} = \pm\ 0.16$, where ε_L is the error in the measurement of wavelength, are indeed acceptable for this typical situation. However, there are several points which are required to be clarified.

ε, meters	U,meter/sec	Percentage of error
0.1	0.6	- 40
0.2	0.65	- 35
- 0.5	4.2	+ 320
- 0.2	1.5	+ 50
- 0.1	1.1	+ 10

TABLE 3.2

Percentage of Errors Introduced for Inferring Current by Measurement Errors for $a = 0.75m$, $n = 1$ rad/sec and $U = 1$ m/sec

Error in Wavelength, meter	ε, meters	U, meter/sec	Percentage of error
5	0.1	0.65	- 35
	- 0.1	1.05	+ 5
- 5	0.1	0.6	- 40
	- 0.1	1.0	0
10	0.1	0.7	- 30
	- 0.1	1.15	+ 15
- 10	0.1	0.6	- 40
	- 0.1	1.0	0

TABLE 3.3

Percentage of Errors Introduced, for Inferring Currents, by Measurement Errors in Amplitudes and Wavelengths for $a = 0.75m$, $n = 1$ rad/sec and $U = 1$ m/sec

The first one, of course, is that because wave-current interactions are phenomena of the second order, waves which are effected significantly by the current have wavelengths less than 70m and wave amplitudes less than 1m. Although the required measurement accuracies on wave amplitudes and wavelengths for inferring currents are worse than those for the evaluation of wave forces, the absolute accuracy of measurement requirements for the former are stricter because the waves involved, in this case, are smaller and shorter. Secondly, there are big differences, by referring to Table 3.3, from overmeasurement to undermeasurement. For positive currents, it is desirable to have undermeasurements in wave amplitudes while for negative currents, it is desirable to have overmeasurements. Whereas, it is desirable to have undermeasurements in wavelengths for both positive and negative current situations.

6. INTERNAL WAVES

It is known that the surface currents associated with traveling internal waves can be sufficiently intense to produce modifications of the surface wave structure that are visible both to the eye and to radar as cited by Perry and Schimke (1965) and Polvani (1972). In a series of measurements off San Diego, Lafond (1962) has shown that visible slicks, under certain wind conditions, move with the underlying train of internal waves. A later series of measurements at the same instrumented platform has shown that these slicks are detectable with radar and exhibit phase correlation with the current pattern produced by the internal wave train as reported by Polvani (1972).

Two different mechanisms have been suggested as responsible for the coupling of internal waves, one associ-

ated with changes in surface composition and the other a direct modification of wave structure. A number of researchers have noted the resonant effect that may be expected on a surface wave packet that travels at the same speed as the internal wave train as cited by Hartle and Zachariason (1969), Holiday (1971), Rosenbluth (1971), and Phillips (1971). Since, at resonance, the wave packet is able to travel great distances while remaining at the same phase point of the internal wave, the continuing interaction leads to a continuous energy transfer from internal to the surface waves.

Thomson and West (1972) employed a linear analysis of the interaction, which provided the necessary insight to the development of, otherwise, non-linear phenomena. To demonstrate the modification of a spectrum of linear waves by a traveling current pattern induced by internal wave, they assumed that the incident waves have a $|\vec{k}|^{-3}$ spectrum. This spectral form is chosen to simulate that of a saturated sea, although it is recognized that this linear wave model is not consistent with the concept of a sea limited by non-linear effects. They calculated power spectra (multiplied by $|\vec{k}|^{3}$) at three locations: one ahead of, one behind, and one directly over the internal wave. Their results were obtained by using the WKB approximation with the standing wave pattern created by the reflected wave smeared out.

The calculation shows a number of interesting effects. First, over the internal wave crest, the spectrum is distorted over a rather broad range of wave numbers. The broadening is less ahead or behind the internal wave.

Another effect noticeable is the lack of intense caustic formation. Although a single wave incident on the pattern would show a large amplitude enhancement in the

neighborhood of its turning point (or reflecting point), this is not true when the incident waves are spectrally distributed.

Outside the current region we see the effect of reflected waves. In front of the internal wave the net effect is an apparent depletion of the high wave numbers. This results from the fact that, as the surface waves are overtaken by the internal wave, those that are "blocked" by the current are accelerated and move ahead of the current pattern with decreased wave number.

The opposite effect occurs astern of the internal wave. Here, the reflection process increases the wave number resulting in a strong increase in the high wave number part of the spectrum as compared to fractionally weaker decrease in the low wave number part.

The effects are, indeed, quantities with the magnitude of the second order. To demonstrate the magnitude, let the half width of the internal wave be 50 meters and peak amplitude be 2 meters and let us also assume that this typical internal wave is traveling at 50 cm/sec along a sharp thermocline at 50 meters depth. Let us also consider a surface wave generated some 26 meters behind the crest of the internal wave. Such a surface wave has a wavelength of 74.2 cm and a group velocity of 52.25 cm/sec (2.25 cm/sec relative to the internal wave). In 50 seconds (64 wave periods), this surface wave will move to a point 1.12 meters closer to the internal wave crest. During this time, its mean square amplitude and slope will be enhanced by the factors 1.23 and 1.30 respectively.

All these numerical quantities indicate that, 5 cm and 10 cm accuracies in wave amplitude and wavelength, respectively, are quite meaningful for the internal waves. The effects of the internal waves on the regular

surface waves, however, can be extended well into the short gravity waves range which cause unwanted "disturbances" or "noises" in the backscattered information (Brown, 1977) collected by ROMS' active microwave sensor. Although the upper bound of these noises can be established theoretically, it is nevertheless not clearly defined in the practical situation. Fortunately, as indicated by Brown (1977), these noises in the backscattered information can be neglected if the looking angle of the sensor is within approximately 20 degrees from the nadir.

IV. MEASUREMENT ACCURACY AND SENSOR PERFORMANCE REQUIREMENTS

1. Measurement Accuracy Requirements

As it can be readily concluded from Section II, an ocean wave is uniquely defined, in the directional spectra, if its wave amplitude a, wavelength L, and the direction of wave propagation θ with respect to the arbitrary direction opposite to the wind are known. However, in Section III, all the measurement accuracy requirements are defined on wave amplitude and wavelength and nothing has been said on the measurement accuracy requirements on θ which is the direction of wave propagation opposite to the wind. That is not because the measurement accuracy requirements on θ are unimportant or irrelevant, but because it is more appropriate to discuss these requirements in this section.

It is desirable to tabulate all the accuracy requirements on wave amplitudes and wavelengths in Table 4.1 for various applications as discussed in the previous section. The accuracy requirements on wavelengths for the first four applications, due to their magnitudes of the first order, are not derived rigorously, but are set on the basis of their applicable ranges in terms of wavelength. The asterisk in Table 4.1 indicates those cases which are

Physical Parameters	Order of Magnitude	Accuracy Requirement		
		Range	Error in Wave Amplitude	Error in Wavelength
Wave Force	1st	$a < 0.5$ m $L < 25$ m	*	*
		$0.5\ \text{m} \leq a \leq 10$ m $25\ \text{m} \leq L$	$-0.1\ \text{m} \leq \varepsilon \leq 0.1$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
		$10\ \text{m} < a$ $25\ \text{m} < L$	$-0.5\ \text{m} \leq \varepsilon \leq 0.5$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
Surface Information for Missiles Launching from Undersea	1st	$a < 0.5$ m $L < 25$ m	*	*
		$0.5\ \text{m} \leq a \leq 10$ m $25\ \text{m} \leq L$	$-0.1\ \text{m} \leq \varepsilon \leq 0.1$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
		$10\ \text{m} < a$ $25\ \text{m} < a$	$-0.5\ \text{m} \leq \varepsilon \leq 0.5$,	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
Fleet Protection	1st	$a < 0.5$ m $L < 25$ m	*	*
		$0.5\ \text{m} \leq a \leq 10$ m $25\ \text{m} \leq L$	$-0.1\ \text{m} \leq \varepsilon \leq 0.1$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
		$10\ \text{m} < a$ $25\ \text{m} < L$	$-0.5\ \text{m} \leq \varepsilon \leq 0.5$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
Wave Prediction	1st	$a < 0.5$ m $L < 25$ m	*	*
		$0.5\ \text{m} < a \leq 10$ m $25\ \text{m} \leq L$	$-0.1\ \text{m} \leq \varepsilon \leq 0.1$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
		$10\ \text{m} < a$ $25\ \text{m} < L$	$-0.5\ \text{m} \leq \varepsilon \leq 0.5$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
Current	2nd	$a \leq 1$ m $L \leq 75$ m	$-0.1\ \text{m} \leq \varepsilon \leq 0.1$ m	$-10\ \text{m} \leq \varepsilon_L \leq 10\text{m}$
		$1\ \text{m} < a$ $75\ \text{m} < L$	————	————
Internal Waves	2nd	$a \leq 0.1$ m $L \leq 5$ m	$-0.05\text{m} \leq \varepsilon \leq 0.05\text{m}$	$-0.1\text{m} \leq \varepsilon_L \leq 0.1\text{m}$
		$0.1\ \text{m} < a$ $5\ \text{m} < L$	————	————

TABLE 4.1
Accuracy Requirements for various physical parameters

of the secondary importance and whose spectral information is desirable to be known. Whereas, the long bar in Table 4.1 indicates those cases which are irrelevant to that particular application.

The measurement accuracy requirements on θ, the direction of wave propagation, are determined on the sensitivities of the various applications to the wave energy distribution which is a function of θ. The wave energy distribution can be isotropic, anisotropic, or unidirectional or any combination of the former three types. In the situation when the wave energy is isotropically distributed, the wave propagates uniformly over all angles and in all directions, even in the directions against the wind. When the wave energy is distributed anisotropically, the wave propagates over a narrow range of angles or directions. The unidirectional wave energy distribution is caused by wave travelling in one direction.

For wind-generated waves, if the ratio of wind speed to phase speed of the wave is much greater than the unity, say, for those waves whose wavelengths are in the short wave range, the energy associated with this particular wave tends to be distributed isotropically. As this ratio of wind speed to phase speed of the wave decreases, the energy associated with the wave has the increasing tendency of being distributed anisotropically with the wind. Because of the long distances travelled by swells their wave energy distributions are unidirectional.

These descriptions on wave energy distributions are certainly simple, to say the least, for the otherwise very complicated random wave field in the ocean. As simple as these descriptions on the wave energy distribution are, it is quite obvious that the wave energy distribution is the function of wind condition, wind speed, wavelength, history

of the wave, and the angle θ. So is the measurement accuracy requirements on θ. That is to say that, for rigorous scientific purposes, there is no single measurement accuracy requirement on all values of θ. However, in practice, there are several reasons which justify the use of single measurement requirement on all values of θ: (1) Isotropic wave energy distribution, which has no directional preference, dominates over the small and short waves range, (2) Waves with anisotropic wave energy distribution travel in a continous band of angles or directions albeit they are narrow, and (3) Swells usually have long wavelengths and are generally unidirectional.

In order to derive this measurement accuracy requirement, it is advantageous to take a typical wave, with wave period of 6.28 seconds and wavelength of 61.5 meters, in the ocean for discussion without the loss of generality. With a typical wind speed of 10 meters per second in the ocean, from Phillips (1969), the resonant angle θ_R with respect to the wind direction for this typical wave can be evaluated as

$$\theta_R = \cos^{-1}\left(\frac{\sqrt{gL/2\pi}}{W} \right) = \pm\, 11.65^{\circ} \tag{4.1}$$

where W is the wind speed. An error of $\pm\, 5^{\circ}$ is indeed acceptable to θ_R, especially, if the instrument provides redundant information by overlapping techniques. By using Equation (4.1), this error of $\pm\, 5^{\circ}$ on θ_R can cause an error from -2.35 meters to +2.05 meters on wavelength which is admissible by referring to Table 4.1. Since θ_R is the complementary angle to θ, the admissible error of $\pm\, 5^{\circ}$ for θ_R is also the admissible error for θ.

There remains the problem of 180° ambiguity in the directional information as cited in Section II if statistical methods are used in deriving the directional spectra.

This ambiguity can be fully or partially compensated if wind velocities are obtained simultaneously. Nevertheless, information on wind velocity is essential to the generation of waves, and thus, is required to be measured with a comparable accuracy.

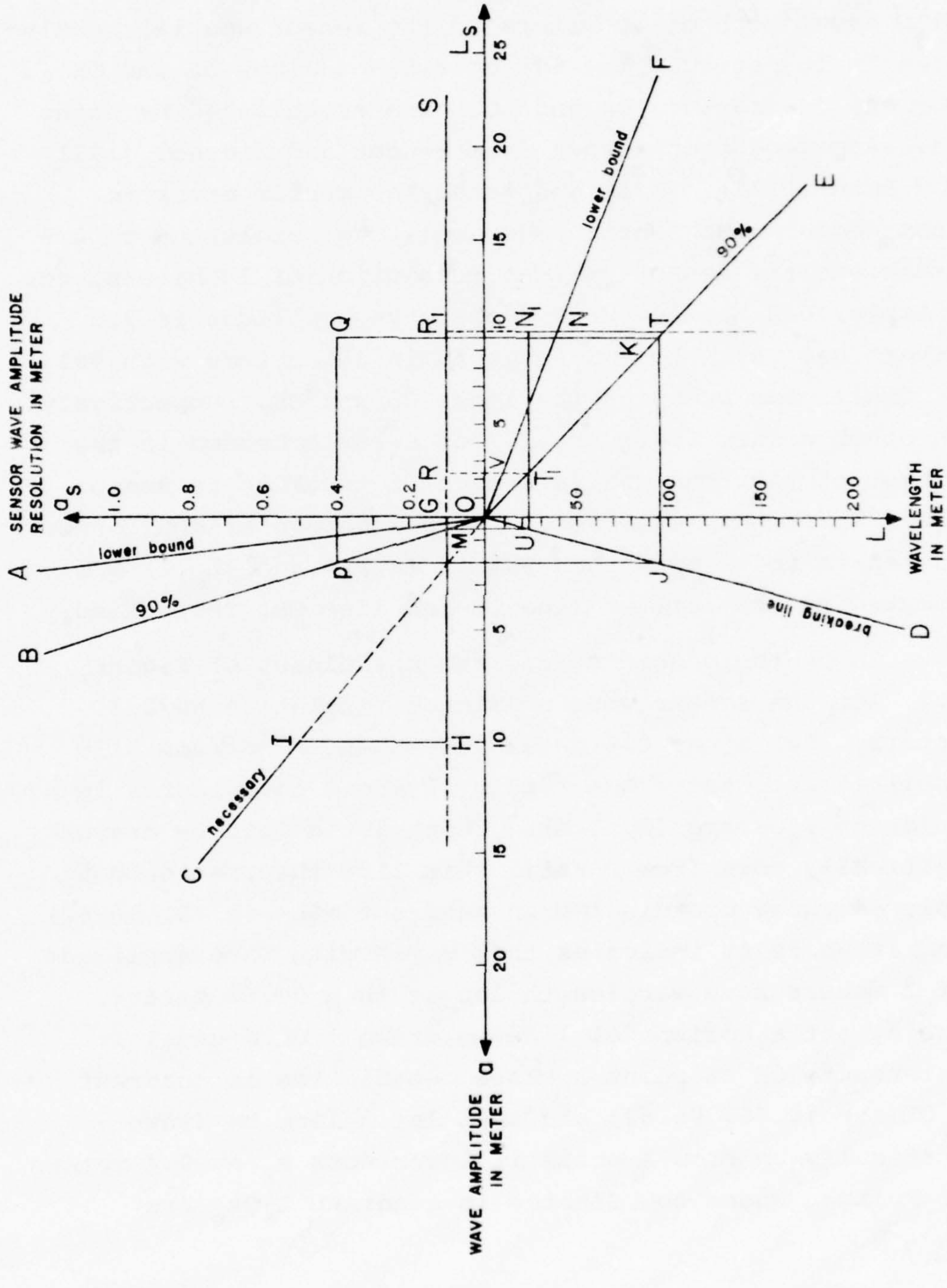
2. Sensor Performance Requirements

The derivation of sensor performance requirements, which are necessary to meet the measurement accuracy requirements on wave amplitude and wavelength as stated in Table 4.1 and on θ as stated in the previous two paragraphs as $\pm 5^{\circ}$, is based upon data processing techniques. These performance requirements can be best illustrated by Figure 4.1.

The horizontal axis to the right is the axis for sensor spatial resolution, L_s, and the horizontal axis to the left is for the wave amplitude, a, derived from the measurements. The vertical axis to the top is the axis for sensor wave amplitude resolution, a_s, and the vertical axis to the bottom is for the wavelength, L, derived from the measurements. It should be noted that there is no meaning for negative quantities among these four axes.

From Stoker (1957) a line, OD, can be established in the quadrant aOL for breaking waves. The wave with wave amplitude and wavelength indicated by any combination to the left of this line OD is not possible because the ratio of wave amplitude to wavelength is limited by breaking process as indicated by the line OD.

It takes a minimum of four equal-spaced measurements in order to resolve a wave in a rough form, thus, the lower bounds OA and OF can be established for the quadrants a_sOa and LOL_s, respectively. In the quadrant a_sOa, for example, if the sensor wave amplitude resolution is 0.5



SENSOR WAVE AMPLITUDE RESOLUTION IN METER
SENSOR SPATIAL RESOLUTION IN METER
WAVELENGTH IN METER
WAVE AMPLITUDE IN METER
lower bound
90%
necessary
breaking line

Fig. 4.1

meters, the smallest wave whose wave amplitude can be resolved in a rough form is the wave with wave amplitude of 1 meter. By the same token, the shortest wave whose wavelength can be resolved in a rough form is the wave with wavelength of 40 meters if the sensor spatial resolution is 10 meters. The 90% confidence lines OB and OE for the quadrants a_sOa and LOL_s are established by using the recommendations drawn from Bendat and Piersol (1971) and Bath (1974). With absolutely no sensor error in measurements the sensor wave amplitude resolution of 0.5 meter and the sensor spatial resolution of 10 meters, for example, can resolve wave whose wave amplitude is 2.5 meters and wave whose wavelength is 100 meters with 90% of confidence by using the lines OB and OE, respectively. In other words, there are 10% of error embedded in the output of spectral analysis even if there is no sensor error in the measurements. The percentage of confidence increases to be more than 90% if (a, a_s) and (L_s, L) are located to the left of line OB and line OE, respectively.

In order to demonstrate the usefulness of Figure 4.1, let the sensor wave amplitude resolution be 0.4 meters. Let a_s at 0.4 meters be extended horizontally until it intersects OB at point P whose coordinates in quadrant a_sOa are (2, 0.4). Then, let a line be drawn vertically down from P until this line intersects OD at point J whose coordinates in quadrant aOL are (2, 96.62) and at where it indicates that waves with wave amplitude of 2 meters have wavelength longer than 96.62 meters. Again, let a horizontal line be drawn from J until it intersects OE at point K whose coordinates in quadrant L_sOL are (9.66, 96.62) and then let a line be drawn vertically up from K until it intersects a_s at 0.4 meters at Point Q whose coordinates in quadrant L_sOa_s are

(9.66, 0.4). This rectangular PJKQ with their vertices located in Figure 4.1 and the lines OB, OD, and OE establish several important results:

(1) With sensor wave amplitude resolution of 0.4 meters and sensor spatial resolution of 9.66 meters, the percentage of confidence in resolution is at 90% if the wave has the wave amplitude of 2 meters and the wavelength of 96.62 meters.

(2) If the wave amplitude of this wave is less than 2 meters, the percentage of confidence in resolving the wave amplitude is less than 90%. However, the percentage of confidence in resolving the wavelength of this particular wave whose wave amplitude is less than 2 meters may still be 90% because the combination of a and L has to be located to the right of line OD.

(3) If the wavelength of this wave is less than 96.62 meters, the percentage of confidence in resolving the wavelength is less than 90%. From the line OD the wave amplitude of this wave is less than 2 meters. From (2) it is obvious that the percentage of confidence in resolving the wave amplitude is also less than 90%.

(4) The cost can be attached to point Q, in the quadrant L_sOa_s, at where it stands for sensor wave amplitude resolution at 0.4 meters and sensor spatial resolution at 9.66 meters.

(5) If the sensor spatial resolution is relaxed to be greater than 9.66 meters to accomodate the cost reduction, the system can still resolve wave with wave amplitude of 2 meters in 90% of confidence, but the wavelength of this wave is certainly longer than 96.62 meters.

(6) Let the sensor spatial resolution be 5 meters. The percentage of confidence in resolving the wavelength

of a wave whose wave amplitude is 2 meters and wavelength is 96.62 meters has to be certainly greater than 90%. However, the wavelengths of waves whose wave amplitudes are 2 meters, in the real ocean, are greater and equalled to 96.62 meters. Then, this sensor spatial resolution of 5 meters with the sensor wave amplitude resolution unchanged at 0.4 meters is a overdesign or overkill.

It is very important to notice that all the results concluded above are based upon no sensor error. Since the percentage of confidence in resolution and the sensor error are two independent random variables, the results cited above are also valid if the product of the fraction of confidence in resolution and the fraction of accuracy of the sensor expressed in terms of percentage replaces the percentage of confidence in resolution for the case of no sensor error.

By assuming the precisions of the sensor are the same as the sensor resolutions, from Section III and Table 4.1, a curve GHIC in the quadrant aOa_s and a curve VNTE in the quadrant L_sOL can be drawn as the required sensor performance in order to meet the established measurement accuracy requirements as stated in Section III and summarized in Table 4.1. It is absolutely necessary to show the characteristics of these two curves as below:

(1) In accordance with the preliminary finding in Section III, the relationship between a_s and a should follow a straight line OC. However, due to the difficulties in building sensor with its precision of measurements under 10 cm, a compromise can be established for the required sensor performance as shown by the curve MHIC in which the percentage of confidence in resolving

wave amplitudes under 2 meters has been degraded and the percentage of confidence in resolving wave amplitudes from 2 meters to 10 meters has been upgraded.

(2) At point M where the curve GHIC intersects line OB, the 90% confidence line in the quadrant aOa_s, and whose coordinates are (0.5, 0.1) the same scheme cited for the rectangular PJKQ can be used to construct the rectangular MUT_1R from which the comparable sensor spatial resolution has been indicated to be 2.30 meters. From line RT_1, it is obvious that the percentage of confidence in resolving wavelength decreased from 90% as wavelength, L, also decreases from 24 meters. However, as it has been indicated in Section III and Table 4.1, the percentage of confidence required in resolving wavelength is less than that required in resolving wave amplitude, a line NT can be established at L_s = 10 meters. Then, the line VN which is part of the line OF, the lower bound, and the line TE which is part of the line OE, the 90% confidence line, can be added to the line NT to form the required sensor performance in the quadrant L_sOL.

(3) The curve RS where the point S is extended horizontally all the way to L_s = 48.30 meters, in the quadrant L_sOa_s, can be used to derive the cost of the system. The cost curves can be drawn, in the same quadrant, for different combinations of sensor resolutions L_s and a_s. These cost curves intersect the curve RS at different locations in the quadrant. Evaluating the costs and the percentages of confidence in resolving both wave amplitudes and wavelengths for which these intersecting points on RS stand for the compromised sensor performance requirements with cost can be obtained.

The sensor performance requirements necessary to meet the measurement accuracy requirement on θ are

primarily due to the limitation in the resolution power of the processing techniques. With the current state-of-the-art of the processing techniques, if the sensor can distinguish undermeasurements from overmeasurements consistently there is no additional sensor performance requirement so that the measurement accuracy requirement on θ can be met.

Therefore, the sensor performance requirements stated in Figure 4.1 in addition to the required capability of distinguishing undermeasurements from overmeasurements constitute the requirements of performance on the sensor.

V. CONCLUSION

The measurement accuracy requirements on various applications, which are relevant and essential to the Navy's needs, for ROMS active microwave sensor are delineated based upon their physical significance, physics involved, and their detectability. The sensor performance requirements, in order to meet the required measurement accuracies, are also derived based upon the sensor's precision, resolution and accuracy in the measurements and the percentage of confidence in the processing techniques. The merger of the measurement accuracy requirements and the sensor performance requirements, necessary to meet these requirements on measurement accuracies, clearly link the theoretical and experimental scientific capabilities with those of the instrument development in this important area of concern. From this established linkage a meaningful compromise between these two capabilities can be conjectured with confidence.

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SYMBOLS

R = Correlation Function

$\vec{x}$ = Position Vector

$\vec{r}$ = Spatial Separation Vector

t = Time

τ = Temporal Separation

X = 3-D Directional Wave Spectrum

$\vec{k}$ = Wave Number Vector

σ = Wave Frequency

E = Wave Energy

ρ = Sea Water Density

g = Gravitational Acceleration

a = Wave Amplitude

ε = Error in the Measurement of Wave Amplitude

E_ε = Wave Energy for Wave whose Amplitude contains an Error of ε

C_ε = Coefficient

$\vec{U}_L$ = Water Particle Velocity

z = Depth from the Mean Sea Level

p_f = Pressure Fluctuation

Φ = Directional Wave Frequency Spectrum

Φ_D = Directional Wave Frequency Spectrum after 2 Hours of Dissipation

σ_ζ = Standard Deviation of the Directional Wave Frequency Spectrum

θ = Angle Opposite to the Wind

n = Total Wave Frequency

$\phi(n)$ = One-Dimensional Wave Frequency Spectrum without the Influence of Current

$\bar{\phi}(n)$ = One-Dimensional Wave Frequency Spectrum with the Influence of Current, U

U = Current

$\bar{a}$ = Wave Amplitude for Wave under the Influence of Current, U

L = Wavelength

θ_R = Resonant Angle

L_s = Sensor Spatial Resolution

a_s = Sensor Wave Amplitude Resolution

ACKNOWLEDGEMENTS

The author wishes to thank Mr. B. S. Yaplee and Dr. V. E. Noble for their encouragement in writing this report. Thanks are also due to Miss M. G. Zulueta for the typing and editing and to Mrs. J. M. Ware for her drawing.

The author would also like to thank Navy Air Systems Command for their financial support under NAVAIR Task No. A370/370C/058B/WF 52-553000 to the Naval Research Laboratory.

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